A New Multiphase CFD Erosion Model for Predicting Material Erosion from Sand Slurries

NETL 2021 Virtual Workshop on Multiphase Flow Science

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Solid Particle Erosion

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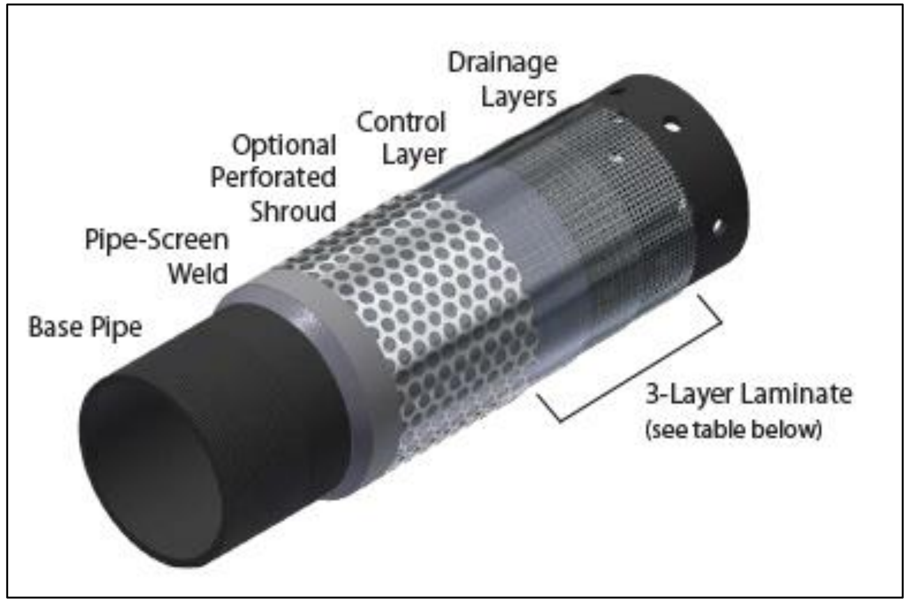
Dynamic process that causes material removal from a target surface due to impingement of fast-moving solid particles

Sand Control Screen



(Porous Metal Filters 2021)

Vehicle Operating in a Desert Environment

(Friedrich 2015)

Powder Abrasive Cleaning

(Chemours 2020)

Erosion Prediction

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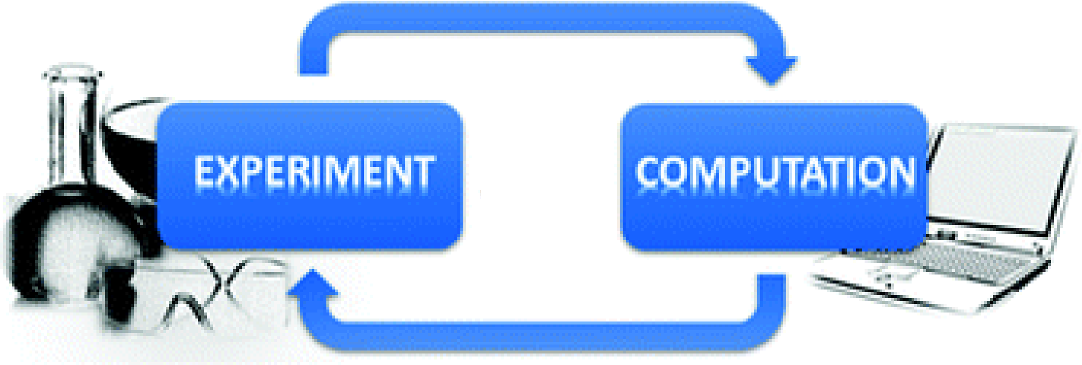
- Can typically be accomplished either through testing programs or with computational fluid dynamics (CFD) multiphase modeling efforts

- Testing can generally be:
  - expensive
  - time-consuming
  - limited in terms of conditions that the facility can handle



- Computational modeling of erosion is a low-cost alternative to testing for preliminary design analysis, but models:
  - are semi-empirical
  - have a low degree of accuracy

Computational Erosion Prediction

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A review of 28 different erosion models provided 33 different input parameters

On average only 5 parameters are used per model

Parameters Selected for Particle Erosion Models

Erodent	Target	Fluid Flow
• Density • Hardness • Moment of inertia • Roundness • Single mass • Size • Velocity • Rebound velocity • Kinetic energy of particle	• Density • Hardness • Flow stress • Young's modulus • Fracture toughness • Critical plastic strain • Depth of deformation • Incremental strain per impact • Thermal conductivity • Melting temperature • Enthalpy of melting • Cutting energy • Deformation energy • Erosion resistance • Heat capacity • Grain molecular weight • Weibull flaw parameter • Lamé constant • Grain diameter	• Impact angle • Impact angle maximum wear • Kinetic energy transfer from particle to target • Temperature

Objective

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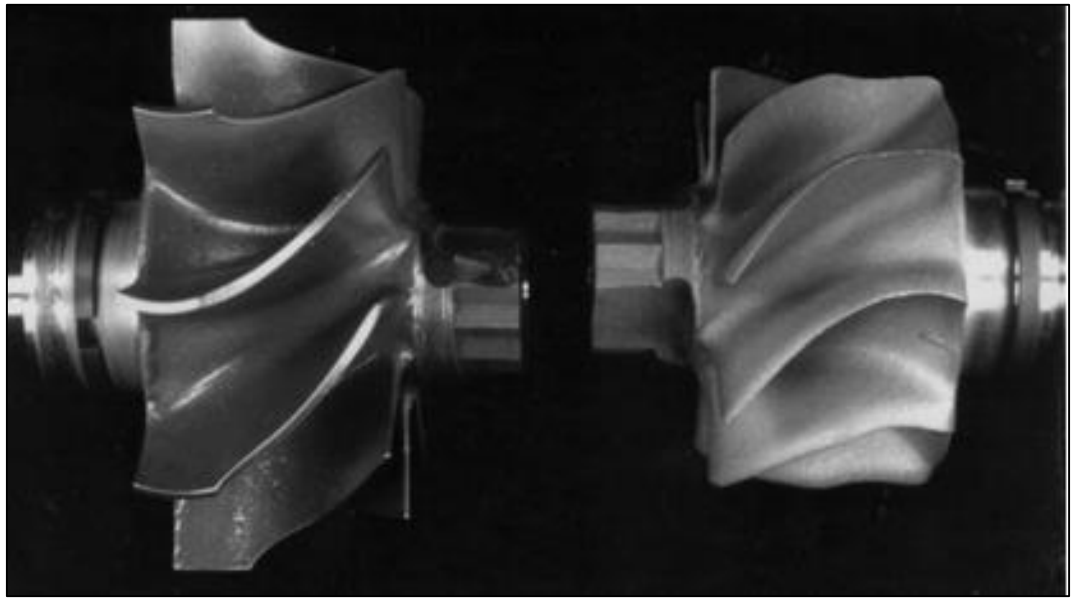
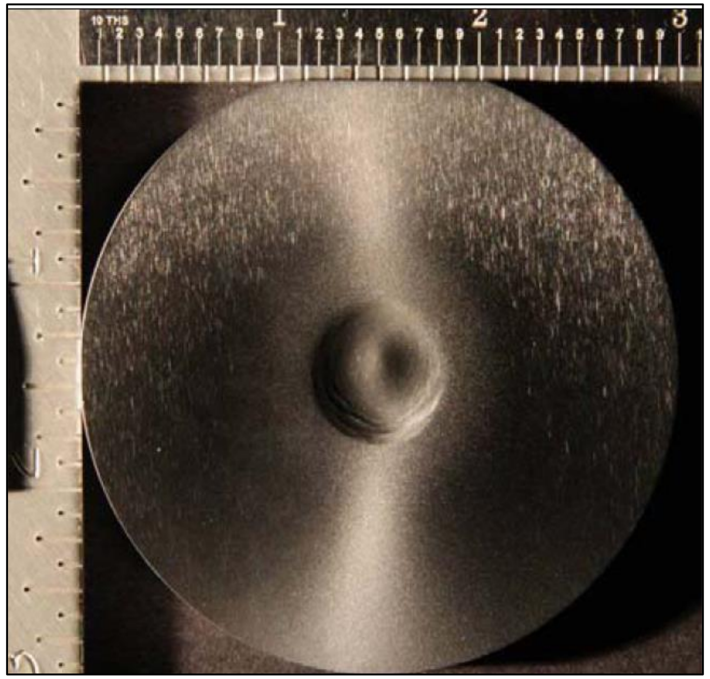
Improve and create a new CFD erosion model by determining the main contributing factors that influence erosion using laboratory-based experiments to refine CFD erosion modeling





Eroded test articles from testing efforts at SwRI

Combination of Validation Testing and Modeling Effort

Recirculating Particle Erosion Test Facility – Jet Impingement Tests

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2013 Study

Angle of impact

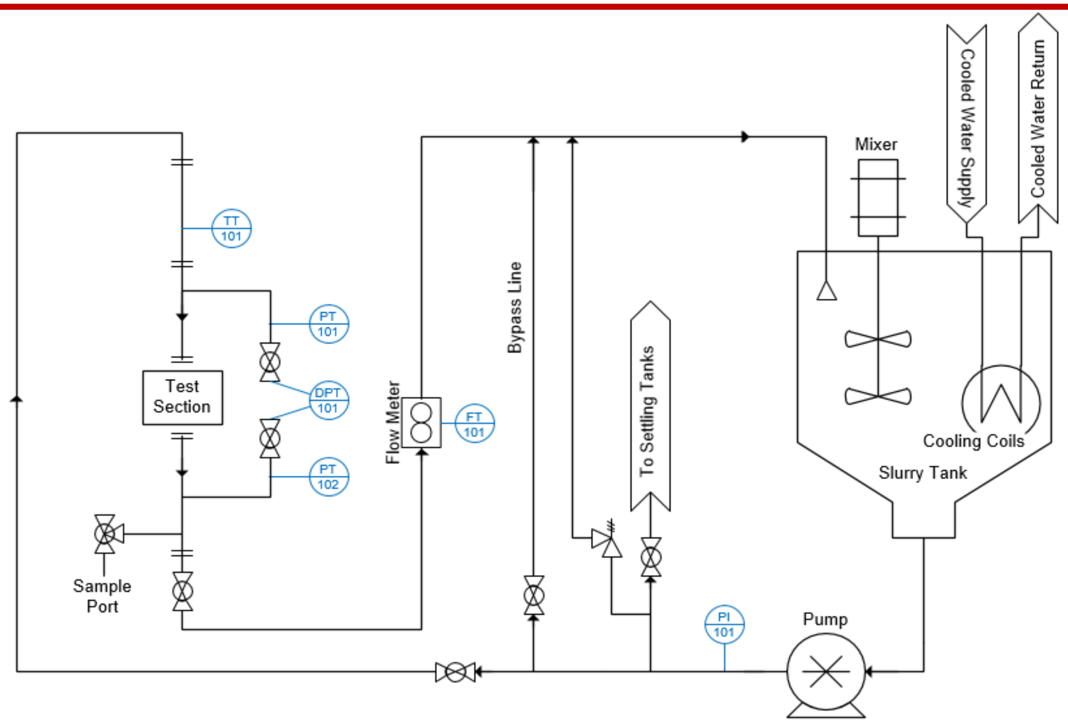
Carrier fluid viscosity

Carrier fluid velocity

Particle concentration

Particle size

Material type



2019 Study

Particle hardness

Particle breakdown

Material type

Material hardness

Impact velocity

Turbulence

Carrier fluid velocity

Carrier fluid flow rate

Technical Approach

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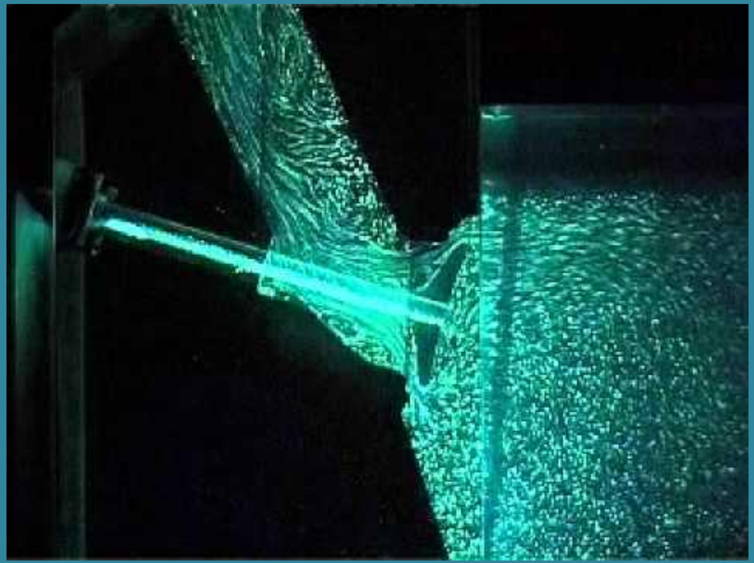
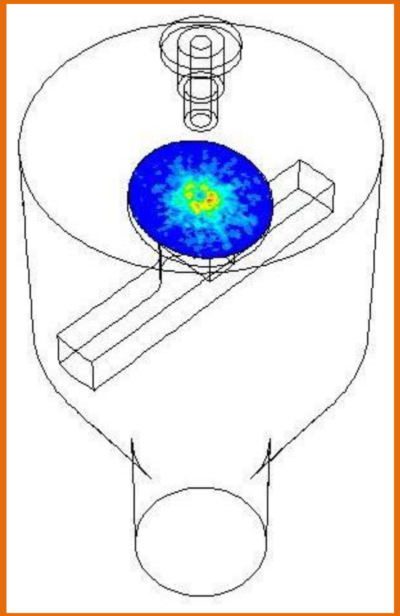
Combination of Experimental Testing and Computational Modeling Effort

Impingement Coupon Analysis

Particle Image Velocimetry (PIV) Analysis



Computational Modeling Analysis



Develop Correlations

Test Facility Configuration

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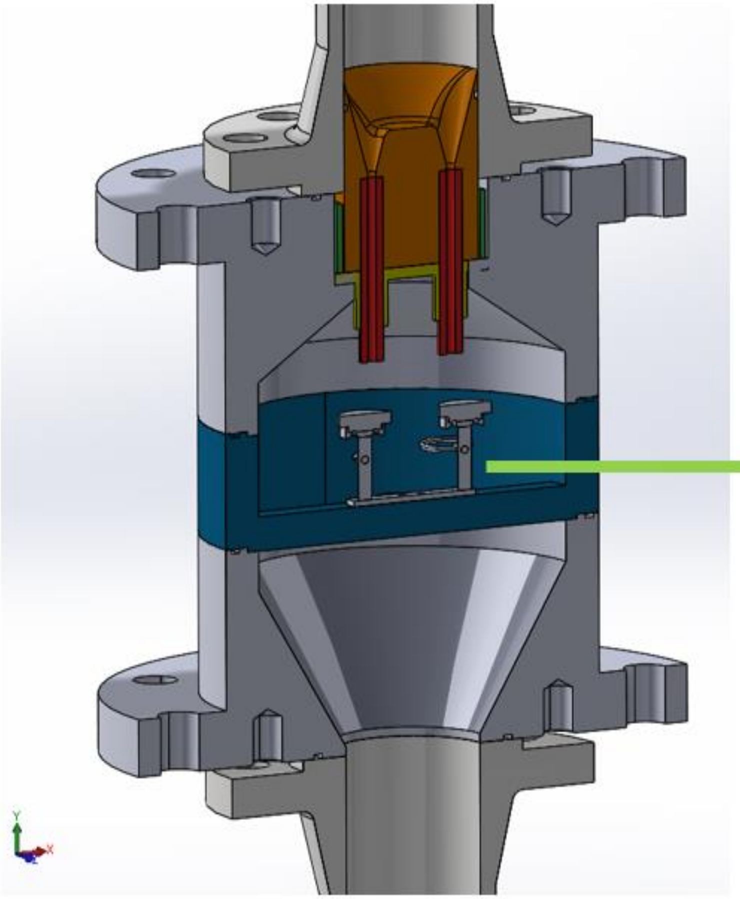
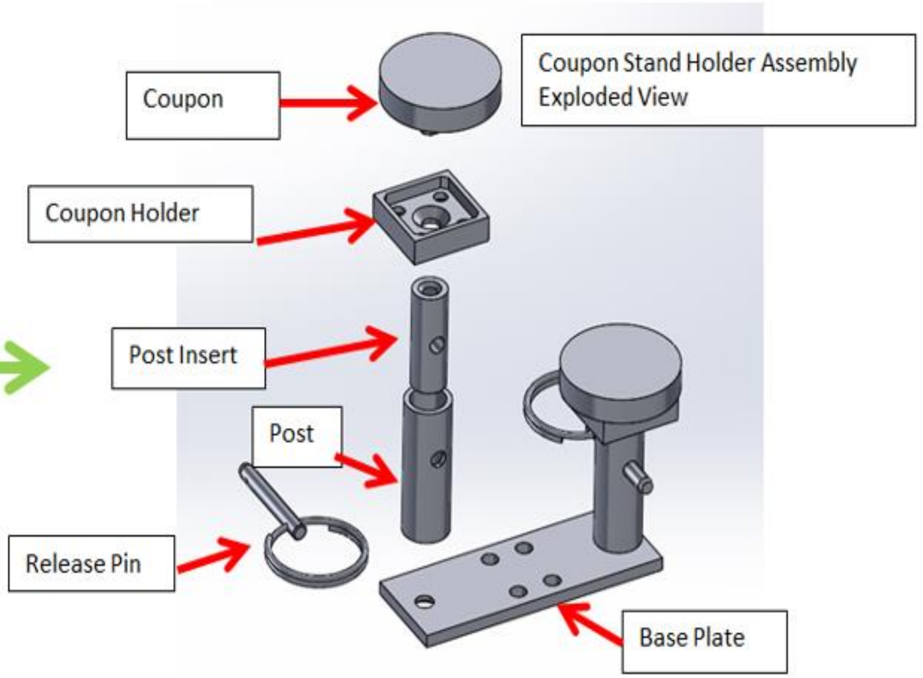
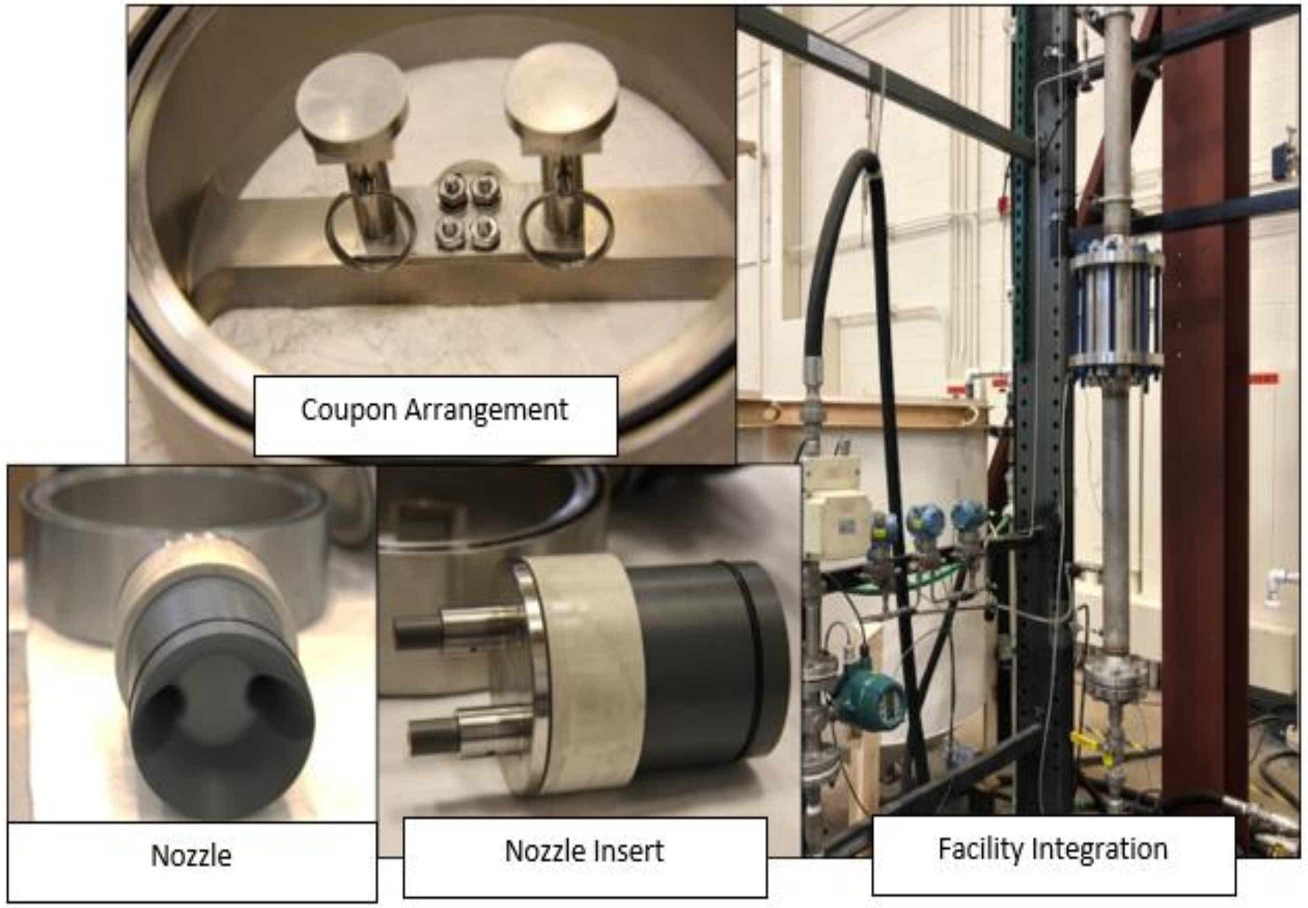
CAD Model of Test Section Arrangement





Facility Integration



Varying Test Conditions

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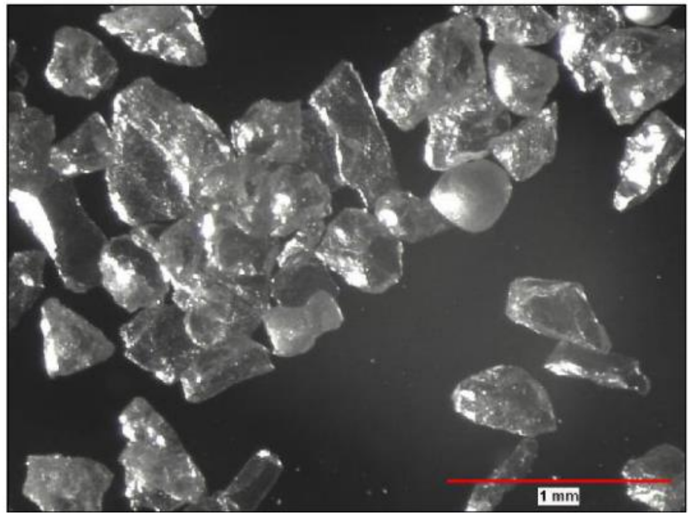
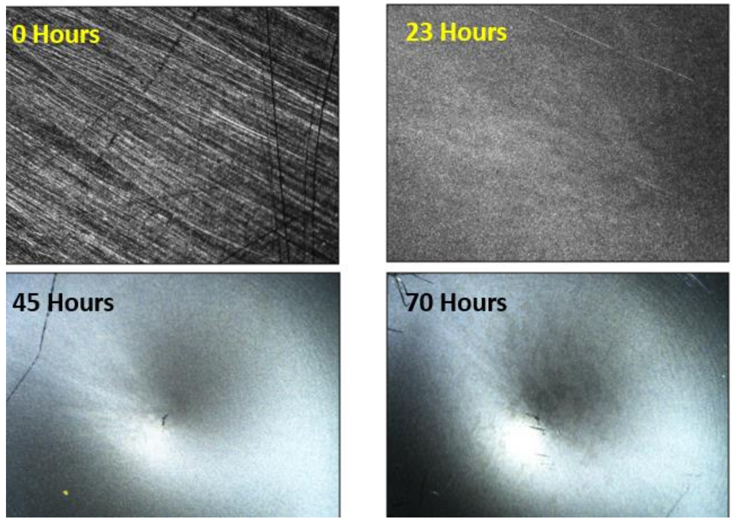
Particle Type	Particle Mean Diameter	Coupon Type	Flow Rate	Particle Concentration	Carrier Fluid Viscosity	Angle of Impact
Silicon Carbide Quartz	89 µm (150-grit) 63 µm (220-grit) 37 µm (280-grit)	Inconel 625 316 Stainless Steel 304 Stainless Steel 6061 Aluminum	12.5 gpm 13.8 gpm 15 gpm 17.5 gpm 20 gpm	1,200 ppm 2,500 ppm 5,000 ppm 7,500 ppm	1 cP 10 cP	20° 40° 60° 80° 90°

- 96-hour test duration
- Test samples pulled approximately 24 intervals
- Particle size distribution measurement
- High-resolution images of particles and coupons

Silicon Carbide Particles



Eroded 316 Stainless Steel



PIV Test Configuration

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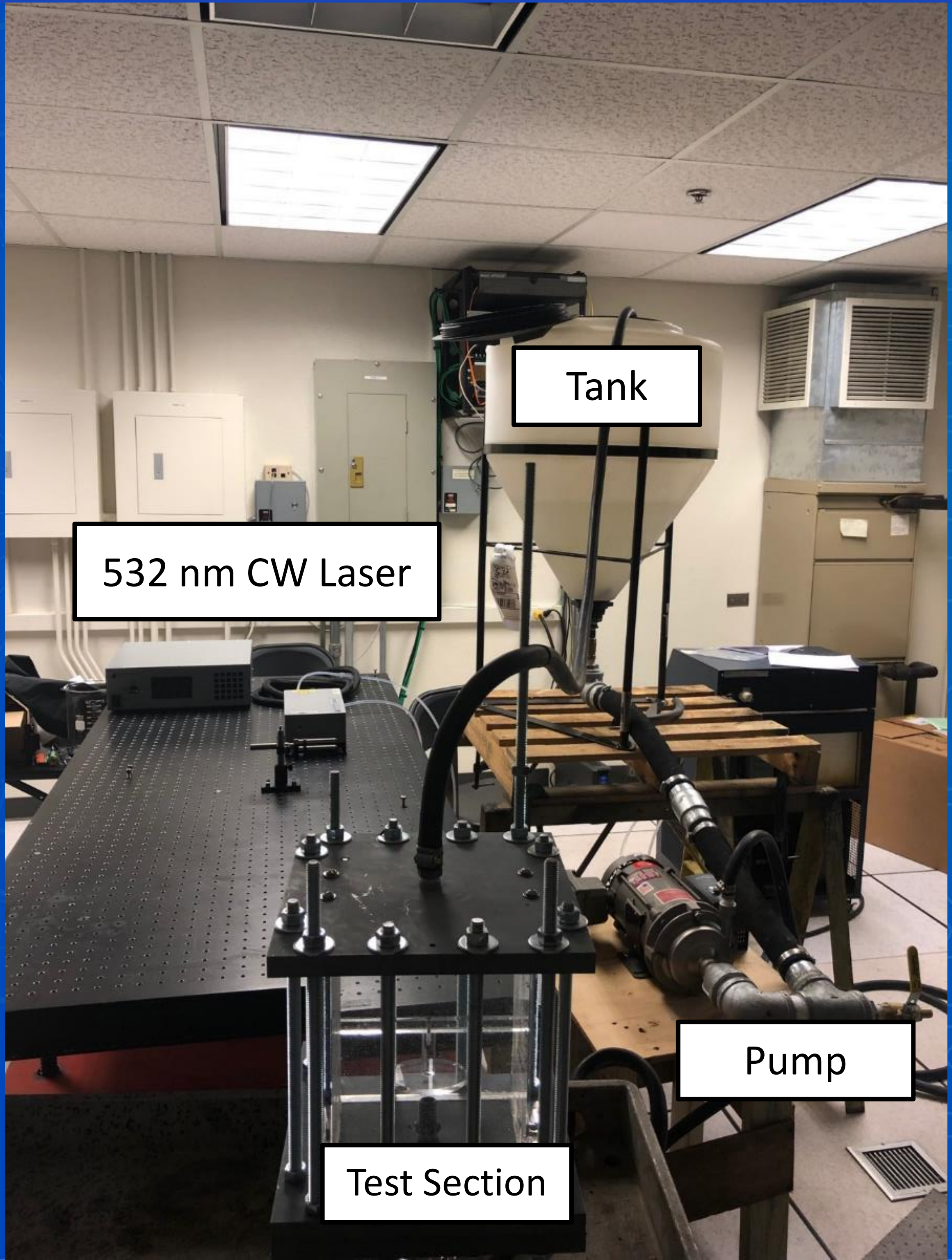

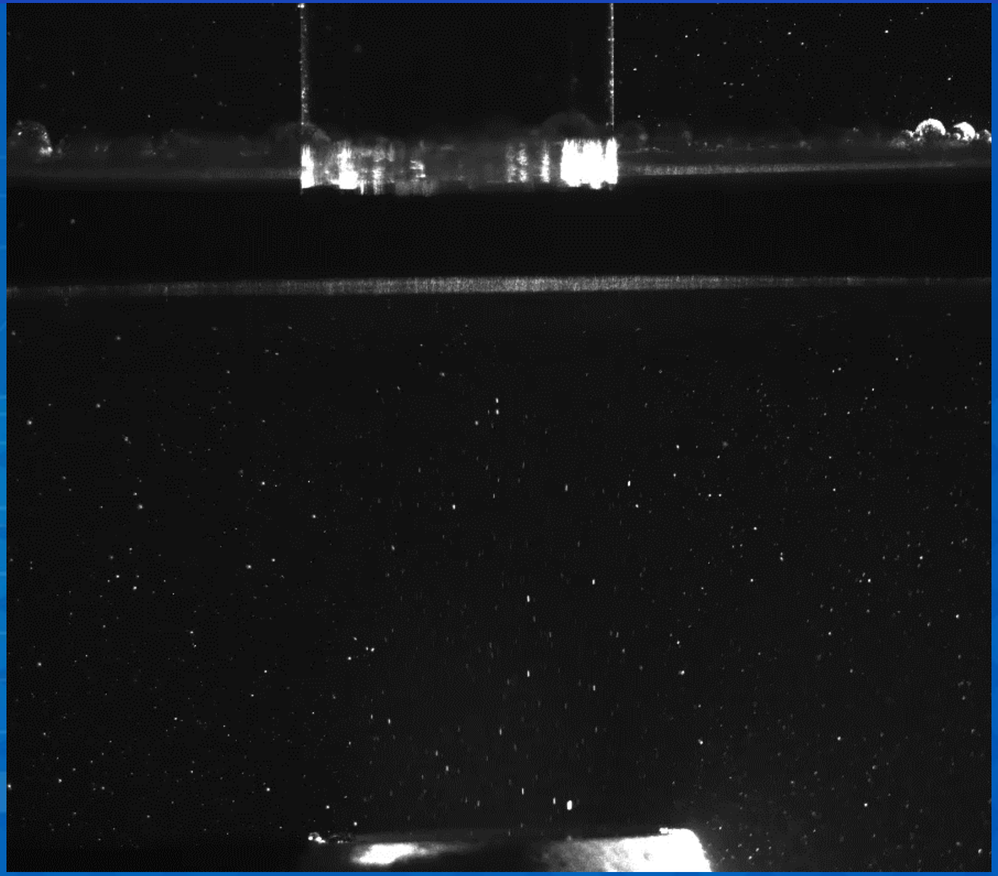

- P-cymene
- 4.5 Watts
- 200 mm macro lens
- 2000 fps
- 0.2 ms exposure
- 1024 x 1024 resolution
- 1.5 GPM

CFD Model and Mesh

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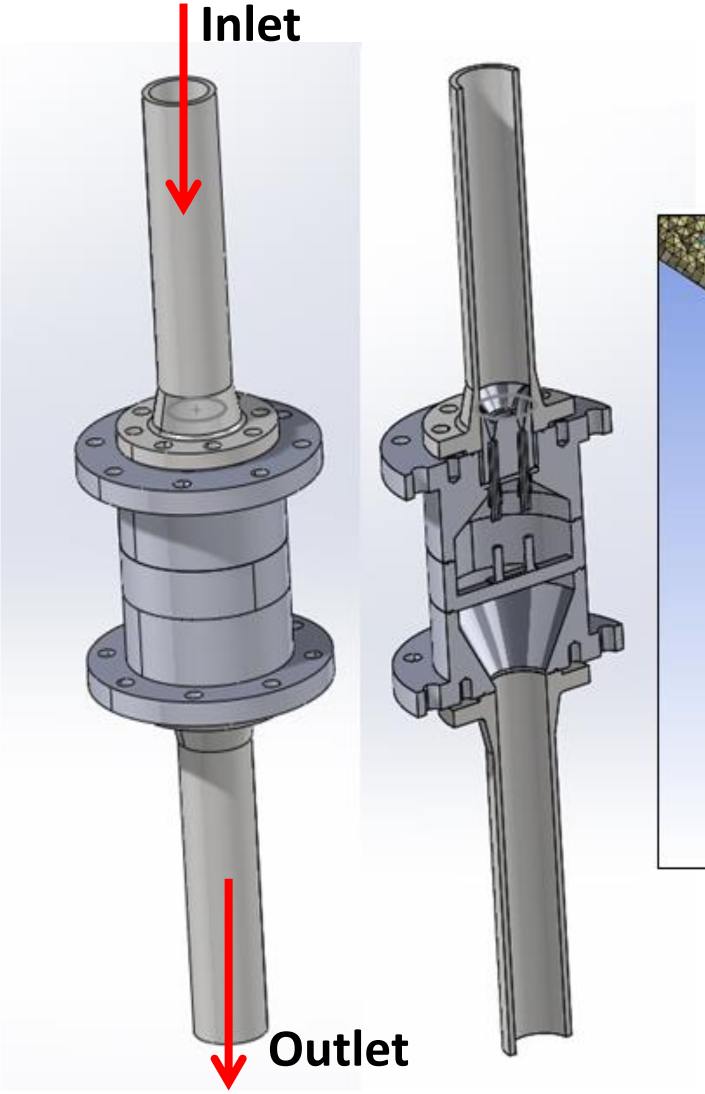
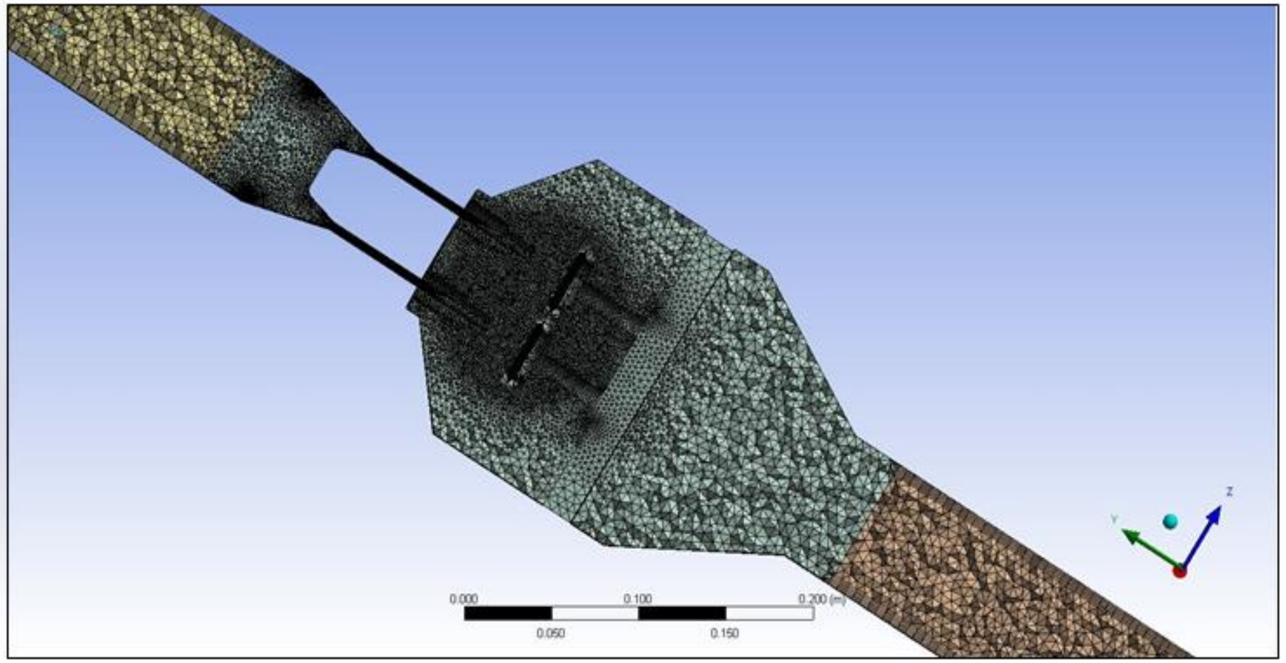
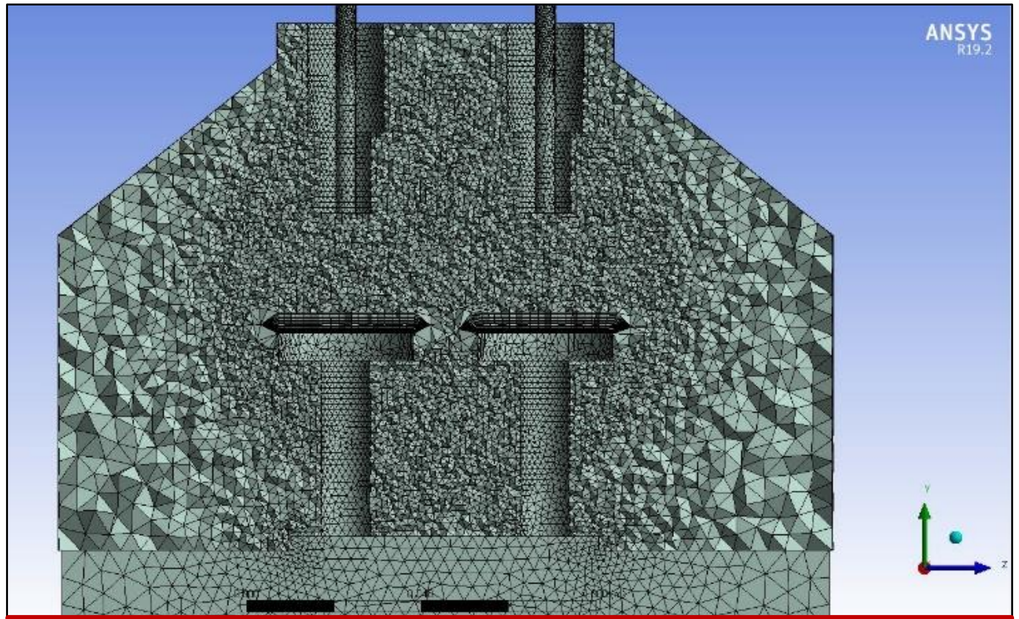


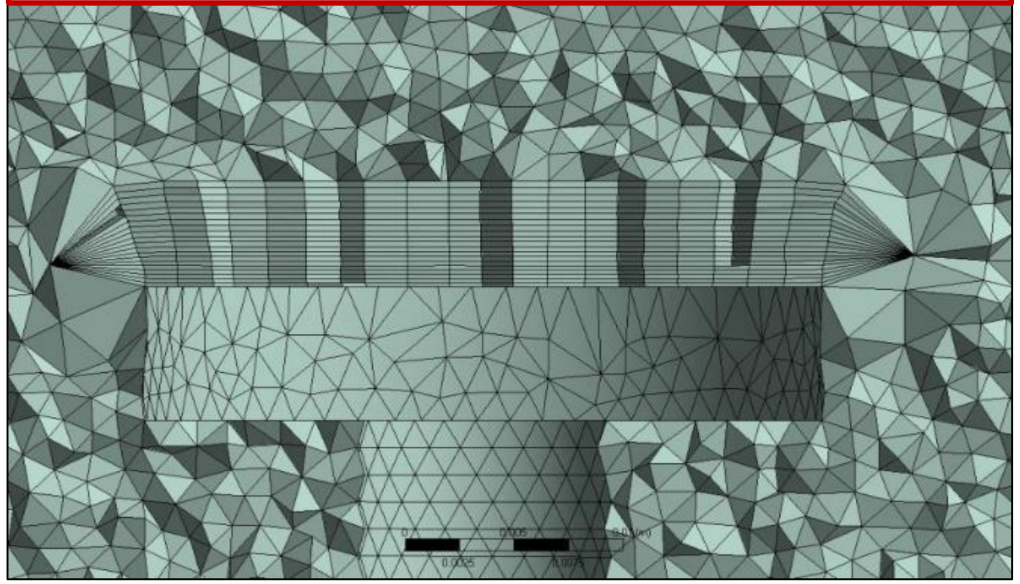
CFD Geometry

Domain Mesh





Mesh Refinement in Regions of Interest



CFD Approach

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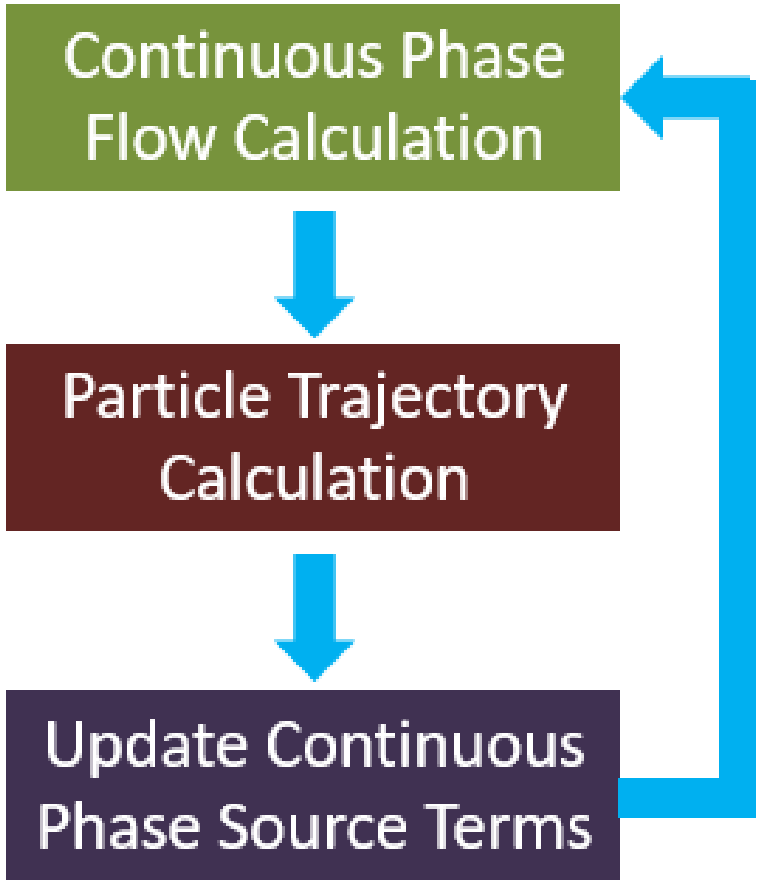
- Analysis conducted in ANSYS® Fluent®
- Eulerian-Lagrangian approach
- Using discrete phase modeling (DPM)
- Stochastic tracking
- C-based user-defined macro analyzed localized erosion rates (kg/m^2-s) at wall boundaries of interest



<u>Multiphase Model Integration</u>

1. Single-phase model only
2. Discrete phase model (DPM) with constant-sized particles
3. DPM with particle size distribution
4. Review default erosion models
5. Integrate SwRI erosion model

Experimental Program Results

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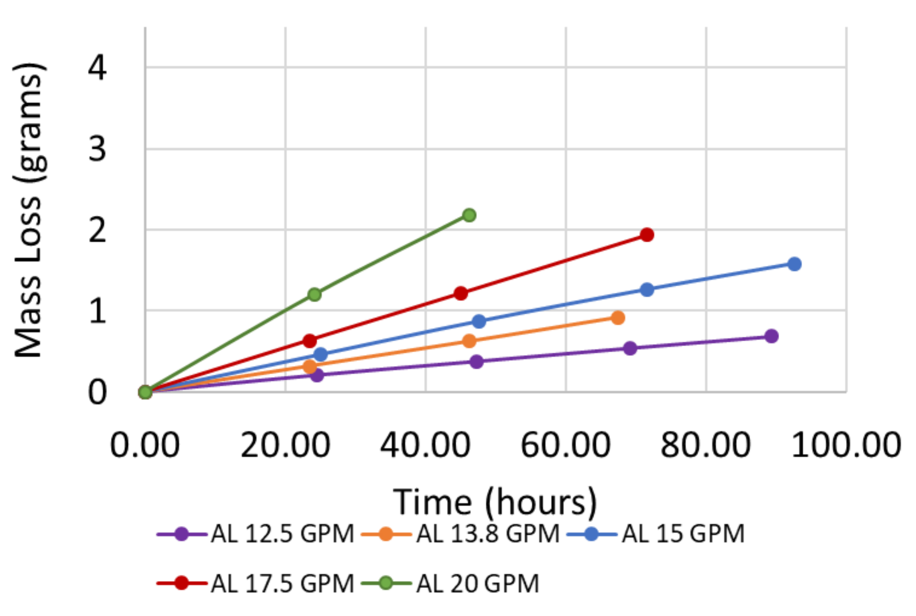
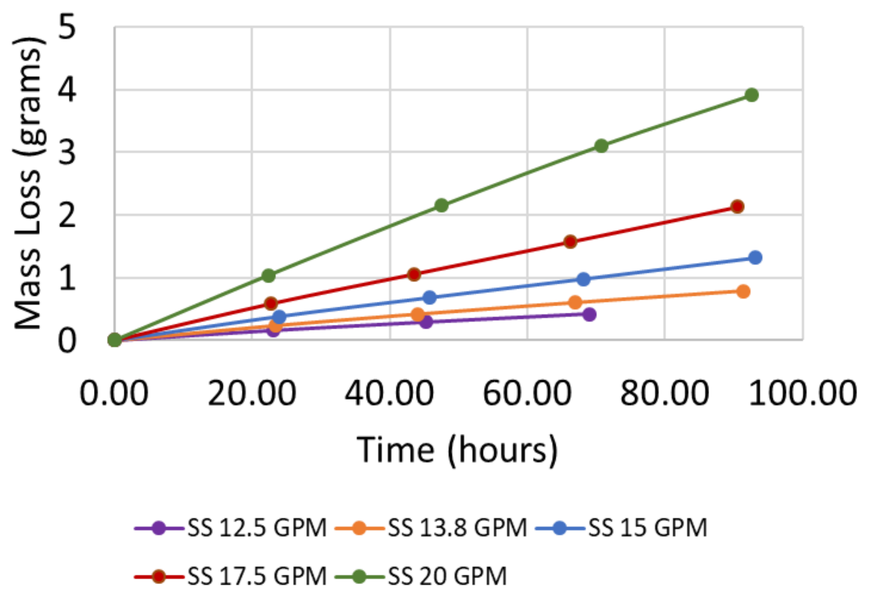
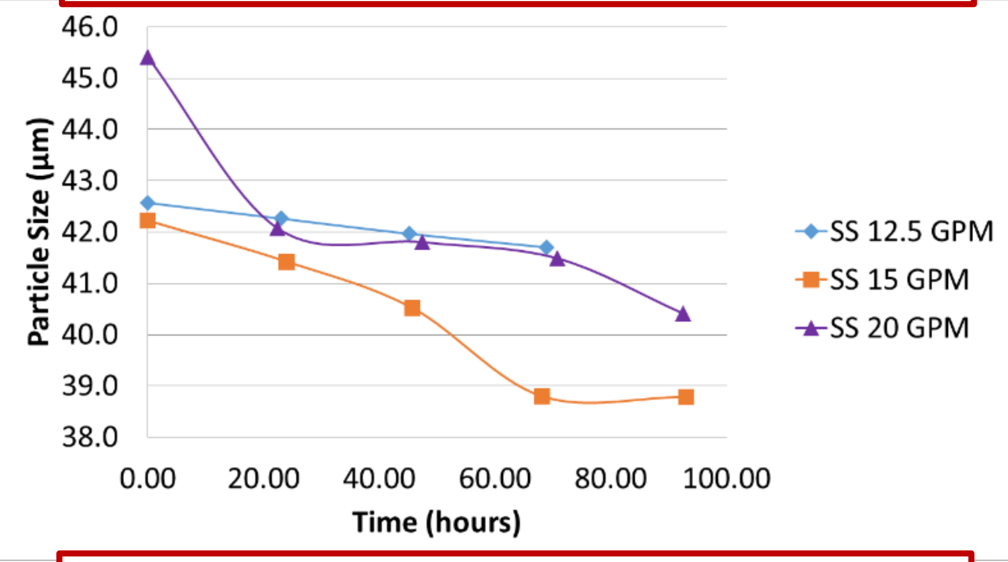
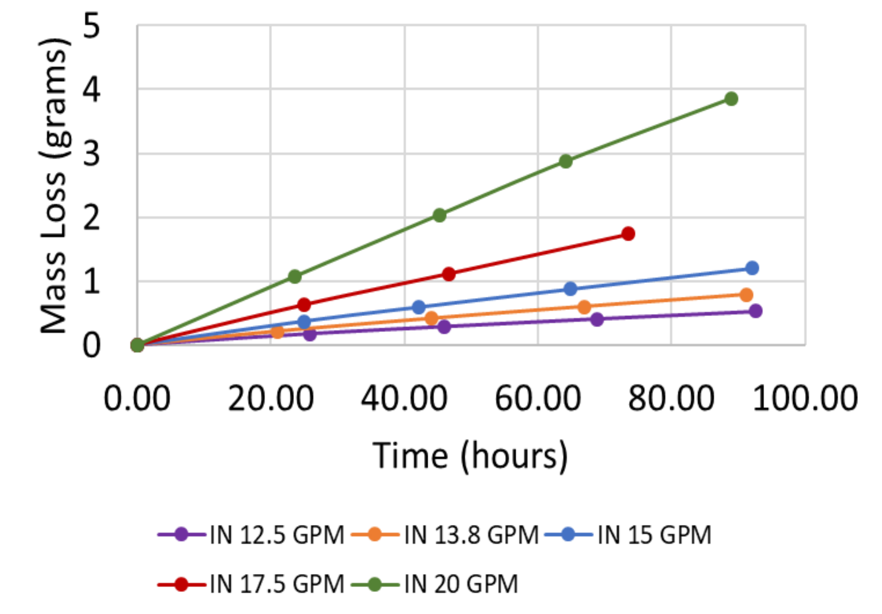




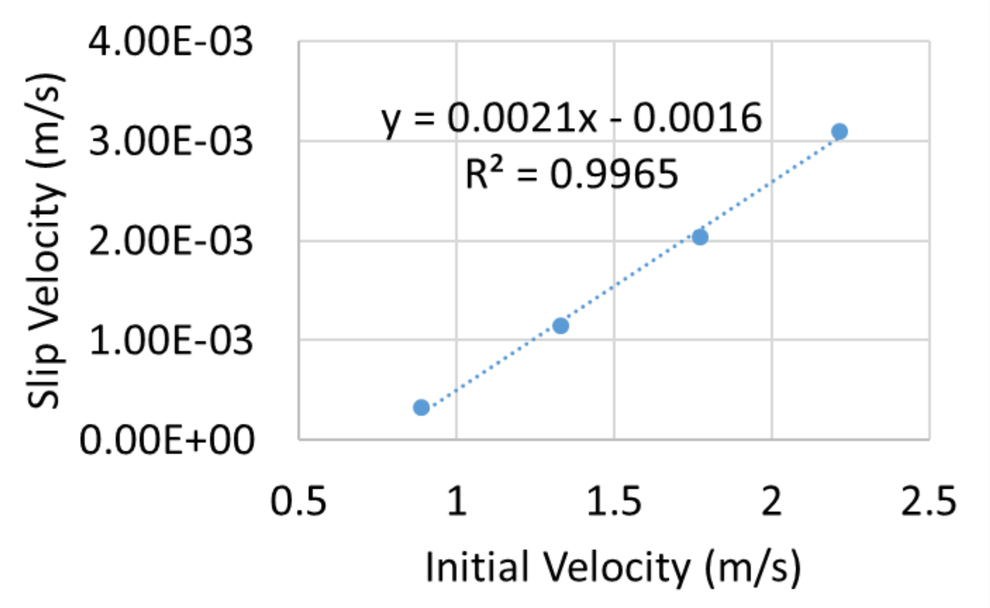
Particle Size Reduction Results



Mass Loss Results



Slip Velocity Results



New Erosion Model

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Equation takes the following form:

$$SE = Kv^n D_p^x B^y f(\alpha) C_0$$

$$SE = \frac{ER_{erosion} A_{face}}{\dot{m}_p}$$

- SE = specific erosion (unitless)
- K = constant coefficient (unitless)
- v = velocity (m/s)
- D_p = particle size (μm)
- B = Brinell hardness = SI form (unitless)
- $f(\alpha)$ = impact angle function (degrees)
- α = impact angle (degrees)
- C_0 = concentration (ppm)
- n, x, y = constants (unitless)
- $ER_{erosion}$ = erosion rate (kg/m^2-s)
- A_{face} = surface area of the impacted wall (m^2)
- $\dot{m}_p$ = mass flow rate of the impacting stream of particles (kg/s)

Comparison Between Default Models

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New Model: $\boldsymbol{SE = 2.3 \times 10^{-17}(0.9978v - 0.0016)^{2.708} D_p^{1.093} B^{-0.379} f(\alpha) C_0}$

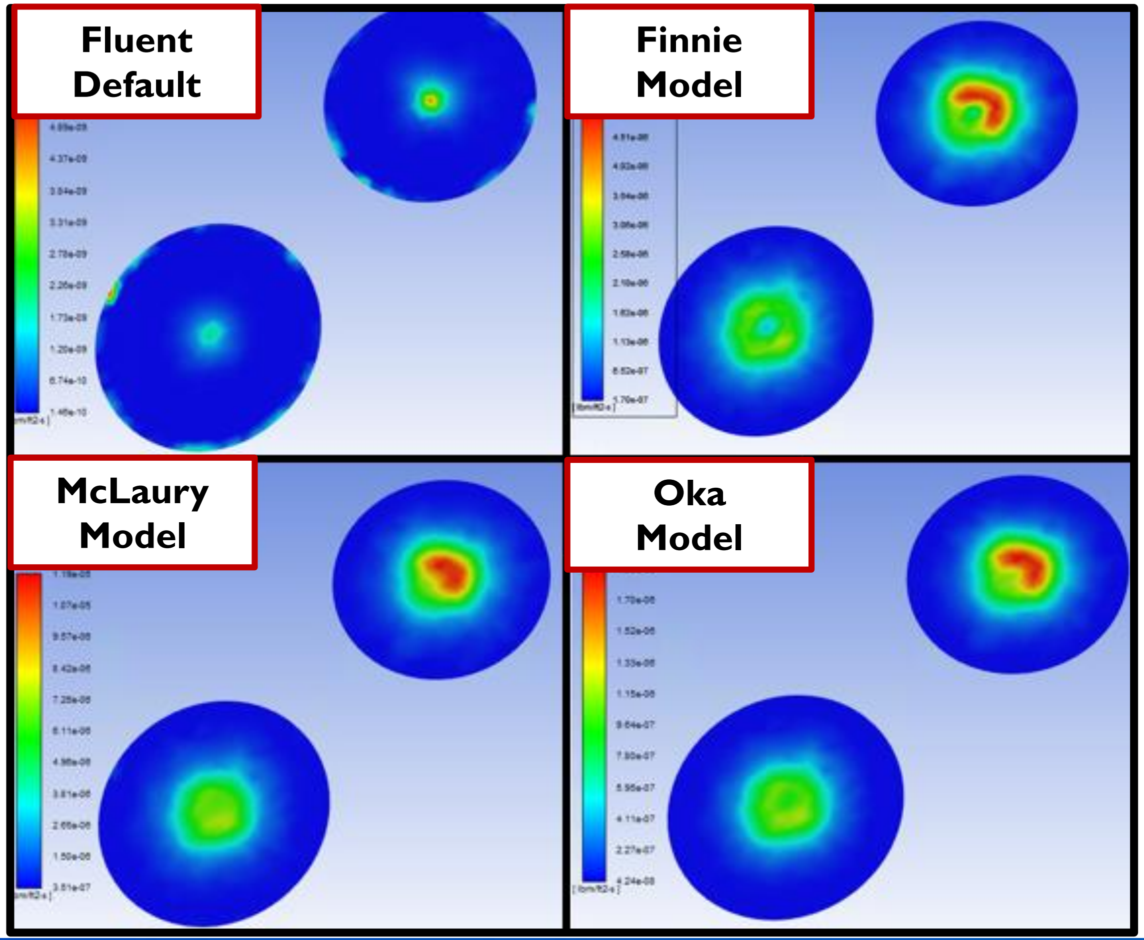
$$f(\alpha) = 9.37\alpha - 42.295\alpha^2 + 110.864\alpha^3 - 175.804\alpha^4 + 170.137\alpha^5 - 98.398\alpha^6 + 31.211\alpha^7 - 4.11\alpha^8$$

For $C_0 < 1{,}570\ ppm$

$$C_0 = 9 \times 10^{-16} C - 5 \times 10^{-13}$$

For $C_0 \geq 1{,}570\ ppm$

$$C_0 = 8 \times 10^{-16} C - 2 \times 10^{-13}$$



Erosion Model	Minimum Erosion Rate (lbm/ft^2-s)	Maximum Erosion Rate (lbm/ft^2-s)	Average Erosion Rate (lbm/ft^2-s)	Percent Difference from Experimental Results
Experimental			3.10×10^{-7}	
Fluent Default	1.46×10^{-10}	5.42×10^{-9}	1.00×10^{-9}	-100%
Finnie	1.70×10^{-7}	4.99×10^{-6}	1.50×10^{-6}	385%
McLaury	3.51×10^{-7}	1.19×10^{-5}	2.50×10^{-6}	708%
Oka	4.24×10^{-8}	1.89×10^{-6}	5.00×10^{-8}	620%

New Erosion Model Results

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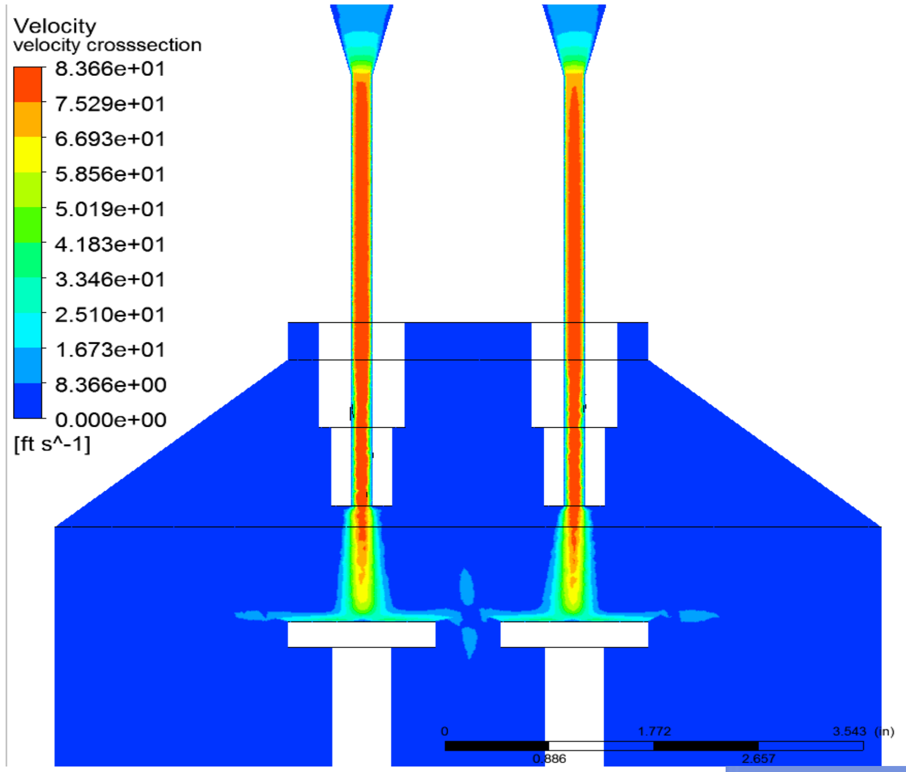
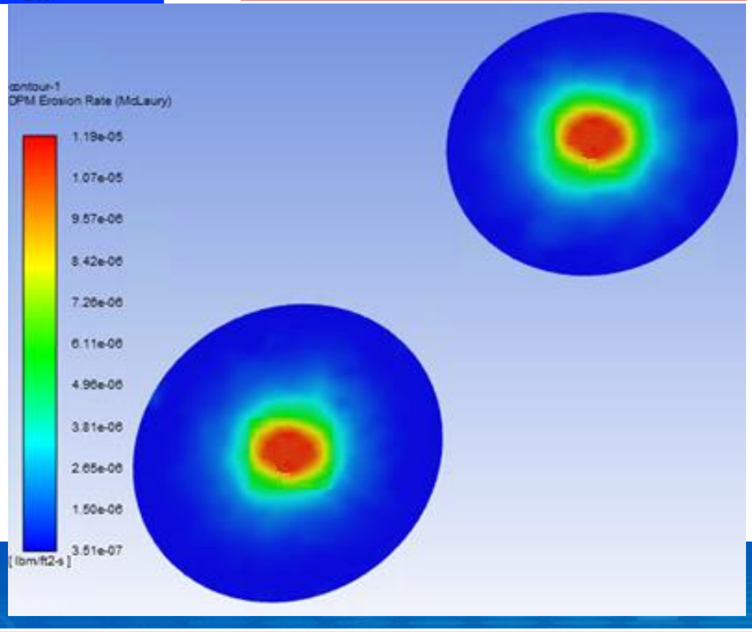
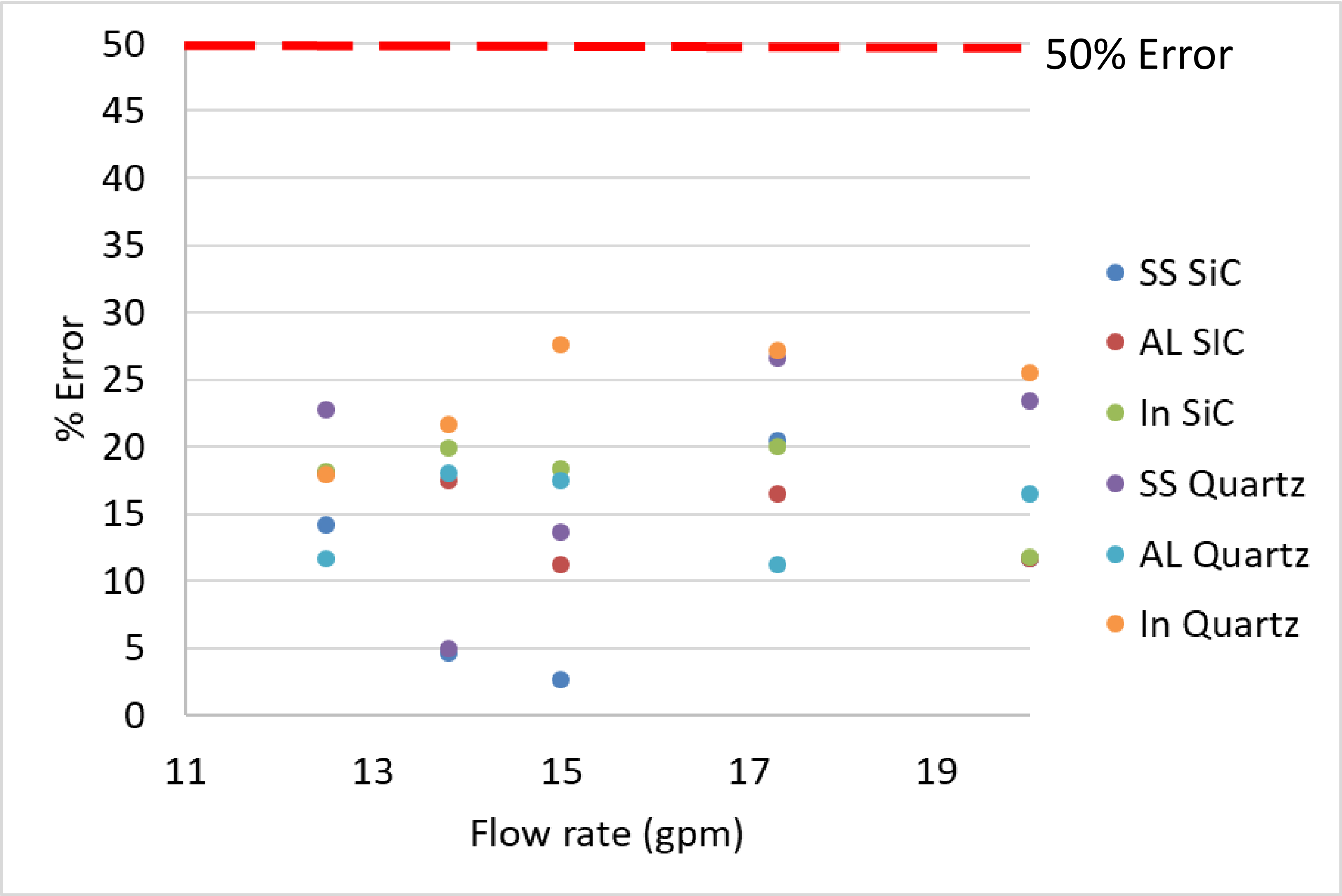


Jet Impingement

Eroded Coupons



Comparison to Validation Data



Summary and Next Steps

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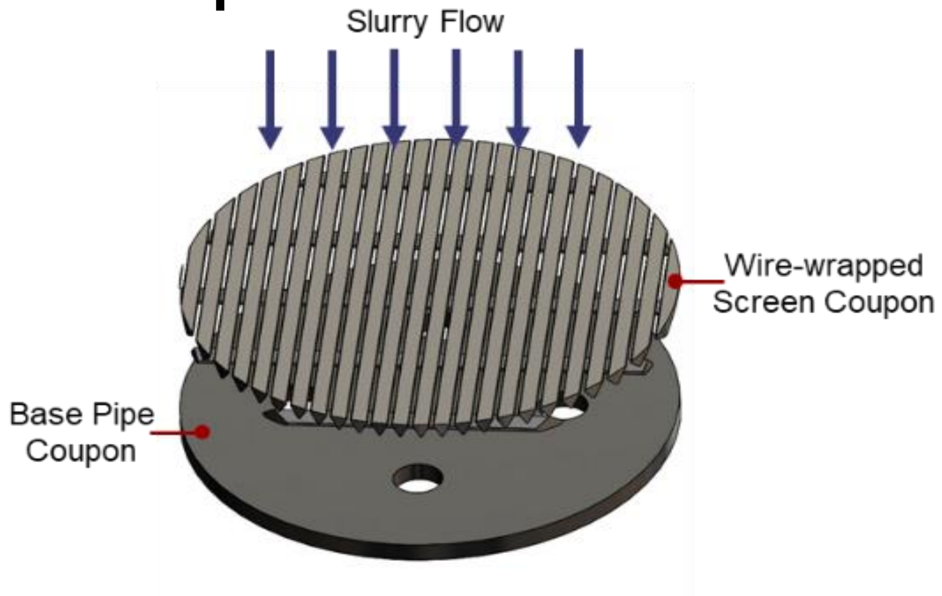
- Validation testing program undertaken to help improve erosion prediction computationally
- Large dataset collected, which helps generate empirical correlations that were integrated into the CFD software to calculate localized erosion rates
- New model demonstrated a 28% agreement with validation data, showing an 25× improvement over commercial software



Currently validating model accuracy on complex geometries

Questions?

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